

HYBRID REFLECTIVE-CRACK RELIEF SYSTEM AT GREATER PEORIA REGIONAL
AIRPORT: A CASE STUDY

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ABSTRACT

Reflective cracking continues to be a major contributor to premature deterioration of asphalt overlays. The design methodologies for asphalt overlays are predominantly empirical, hindered by a lack of fundamental understanding of reflective cracking mechanisms and a shortage of validated damage models. This paper describes a comprehensive reflective cracking study involving instrumented field sections, laboratory testing, and advanced numerical modeling techniques. In coordination with the Illinois Division of Aeronautics, a series of test sections were constructed at the Greater Peoria Regional Airport (GPRA) in central Illinois. In particular, a novel high-performance, partial-depth composite patching method was developed for retardation of reflective cracking over an existing pavement with 50 mm wide thermal cracks. A hybrid reflective crack relief system was designed and installed, which involved a combination of a strain tolerant interlayer mixture used in conjunction with a fiberglass reinforcement grid applied in wide strips. Fundamental laboratory tests, including low-temperature creep, strength, and fracture tests were conducted on overlay and interlayer materials. Finite element analyses of field test sections were conducted, including viscoelastic bulk material modeling and cohesive zone fracture modeling. Results of parametric analyses conducted to calibrate the numerical models to measured responses caused by thermal cycling are presented. Field performance data is also presented and compared to historical performance data relating to traditional overlay systems used at GPRA, showing a significant increase in performance for the new hybrid interlayer system. The comprehensive lab, field, and modeling study provides significant new insight towards the mechanisms of reflective cracking in airfield pavements and its mitigation.

INTRODUCTION

Until 2001, Taxiway E at the Greater Peoria Regional Airport (GPRA) had not been rehabilitated since in 1971 and had developed significant thermal cracking distress. The 75-mm bituminous overlay placed in 1971 had performed beyond its original design life in spite of a significant increase in operations and gross weight for the aircraft normally using the facility. As the leader of a team that included the Illinois Division of Aeronautics, Crawford, Murphy, Tilly and Associates and the FAA- Center of Excellence for Airfield Pavements (COE) at the University of Illinois at Urbana-Champaign, the Greater Peoria Airport Authority prepared an unsolicited proposal for the development, design, construction and monitoring of an innovative rehabilitation project at the GPRA. This paper gives an overview of the GPRA rehabilitation project, describes a hybrid reflective cracking relief system used to repair existing thermal cracks, and presents field cracking performance data as well as the results of a finite element study comparing critical overlay responses.

The airfield diagram for GPRA is shown in Figure 1. The rehabilitated pavement (Taxiway E) is the main parallel taxiway to runway 13-31, which is the most frequently used runway. The rehabilitated section of the taxiway is between junction of Taxiway E with E6 and D (shown in Figure 1). During 2009 approximately 36,000 aircraft operations were conducted at GPRA, with air taxi and commercial aviation as major operators.

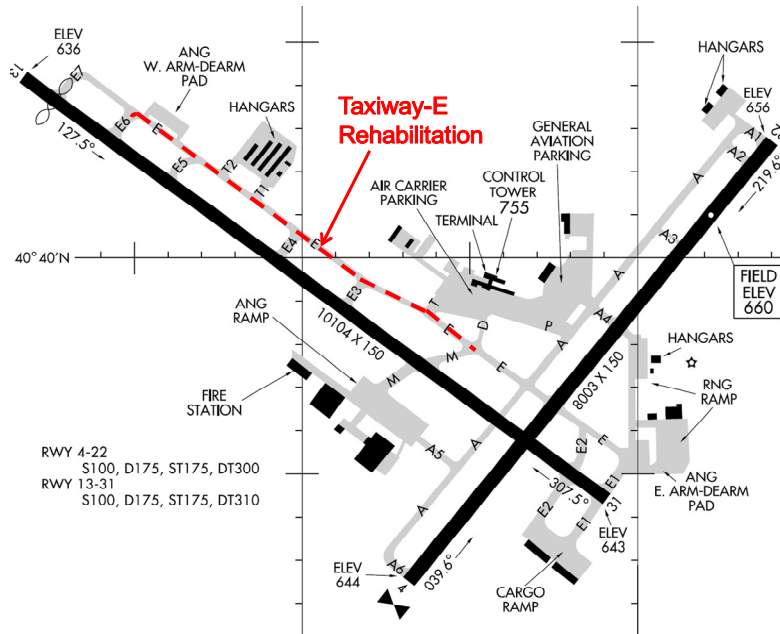


Figure 1. Greater Peoria Regional Airport, Rehabilitated Portion of Taxiway E is highlighted.

DESIGN OF REFLECTIVE CRACK RELIEF SYSTEM

The long service life of the existing bituminous pavement at GPRA resulted in significant environmental damage to the top lift of the existing bituminous surface of Taxiway E. The block cracking was so extensive that it was necessary to specify the removal of the top 50 mm of bituminous surface (Figure 2).



Figure 2. Existing Thermal Cracks on Taxiway E (up to 50 mm wide).

The thermal crack spacing on Taxiway E was fairly widespread (15 to 50 meters), and it was therefore assumed that this wide crack spacing would create a high potential for rapid reflective cracking. Thermally-cracked asphalt pavements, upon thermal contraction during cooling cycles, will tend to shrink from the edges towards the center of uncracked areas. Thermally-induced contractive strains for larger uncracked pavement segments would logically lead to larger crack openings as compared to those associated with shorter segments for a given thermal cycle. When an asphalt overlay is placed over a “working crack,” the opening movements deliver a concentrated tensile stress to the bottom of the overlay, which can lead to reflective cracking. A recent study by Dave and Buttlar [1] explained the non-load associated thermal-reflective cracking mechanisms in asphalt concrete overlays through the use of finite element modeling. In the case of very active working cracks, both base isolation and overlay reinforcement are approaches that can be used retard reflection cracking. Complete, or ‘area wide’ treatment, or strip-type treatments are available. Strip treatments have the potential to be less costly than area-wide treatments, but they must be sufficiently wide in order to avoid the propagation of a reflective crack from the edge of the treatment.

To facilitate a larger reinforcement width and to provide enhanced base isolation benefits, a hybrid reflective crack relief system was designed for GPRA. The system involved the use of a high-strength, self-adhesive, fiberglass geogrid material adhered to a strain-tolerant base isolation layer. The reinforcing layer has a tensile strength in the critical direction of joint or crack opening of over 200 kN/m. Due to the combination of strength, stiffness, and aperture (grid opening) size, GlasGrid 8502 fabric was selected for the hybrid system. This product also has the advantage of a pressure-activated adhesive, which eliminates the need for tack coat placement. Furthermore, the rigidity of GlasGrid, as compared to other strong geotextiles, such as woven polyester, has the advantage of wrinkle-free construction, and eliminates the need for tensioning the fabric during placement. The typical reflective crack control section utilized a 1.5 meter wide reinforcing fabric over a 50 mm thick base isolation interlayer, based upon insight gained by 3D finite element analyses by Kim and Buttlar [2].

The base-isolation layer was designed as a strip-type inlay, as indicated in Figure 3. The use of a strip-type inlay system had two main benefits: 1) reduction of quantities of specialized, costly base isolation materials, and; 2) removal of additional material in the vicinity of existing thermal cracks, which was damaged (spalled) and contained failed sealant materials and debris. The inlay mixture was designed as a 4.75-mm top aggregate size sand-asphalt mix, with a strain-tolerant polymer binder. A preliminary mix design was performed at ATREL, which utilized Superpave PG 70-34 binder at 8% asphalt content, and 3% voids at 50 gyrations of compaction. This mix was designed to have high strain-tolerance and crack resistance at low temperatures, while possessing good stability characteristics at high temperatures, to avoid rutting under design aircraft. During construction, a binder conforming to a Superpave continuous grading of PG 76-31 was utilized.

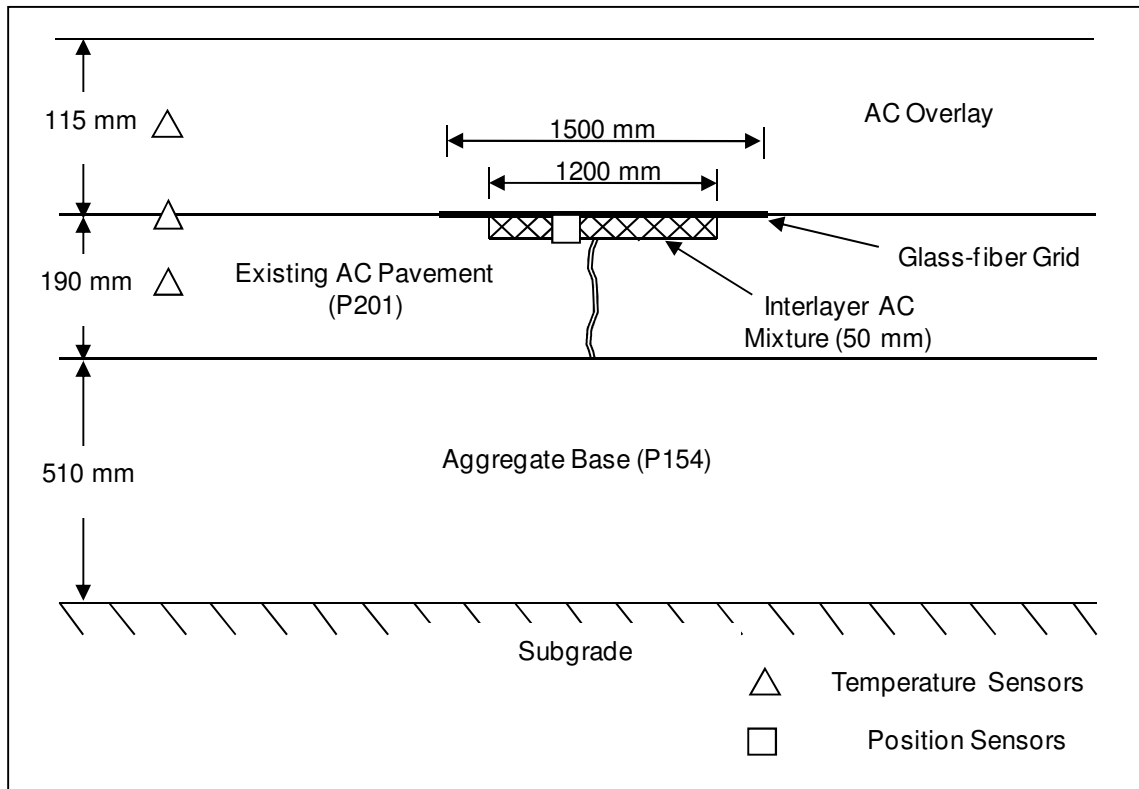
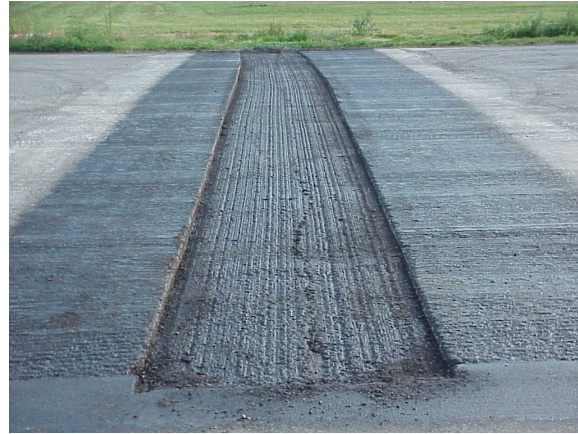


Figure 3. Schematic of Rehabilitation using Overlay and Reflective Crack Relief System.

Figure 4 illustrates the construction sequence of the hybrid interlayer system. After area wide milling of the existing surface, the remaining full-width, full-depth cracks were marked for inlay milling. In some cases, a piecewise linear milling pattern was required, with up to 4 directional changes. However, most of the 70 thermal crack sites on Taxiway E were milled with one or two segments. It was not possible to mill to exactly 50 mm depth, and a range of depths between 25 and 75 mm was actually achieved. However, a range of ± 15 mm from the target was achieved for the vast majority of the project. The polymer-modified sand asphalt mixture was compacted to approximately 3.5 percent air voids in the field, using a narrow, vibratory steel drum roller. The laydown of the GlasGrid 8502 reinforcement was straightforward, aided by the ability of the fabric to tolerate a modest degree of directional change and the functionality of the pressure activated adhesive coating, which avoided pickup under construction traffic.



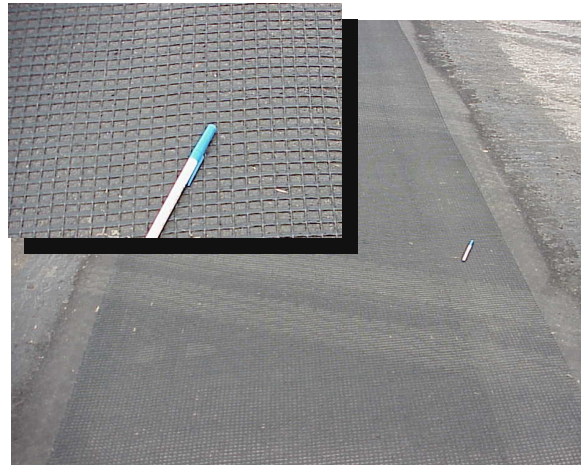
(a) After area milling



(b) Additional 1200 mm by 50 mm milling



(c) After placement of interlayer



(d) With 1500 m wide fiberglass reinforcement

Figure 4. Construction of Hybrid Reflective-Crack Relief System

Pavement sensors were placed before and during construction to monitor temperature, horizontal joint activity, and to detect crack initiation in various locations and depths in the overlay systems used at Peoria. These measurements were critical in helping researchers understand the behavior and performance of rehabilitation alternatives used at Peoria, and more importantly, will facilitate the transfer of these findings into more general overlay design procedures and policies. The sensors used at Peoria included: horizontally aligned linear voltage differential transducers (LVDTs) to measure joint opening and closing of existing thermal crack sites, vertically aligned LVDTs to measure load-related pavement deflections at thermal crack sites, temperature measuring thermocouples, and crack detection foil gages. However, the presentation of field measurement data is beyond the scope of this paper.

MATERIAL CHARACTERIZATION

The focus of the laboratory testing on the Peoria Airport materials was on the low temperature response of the asphalt mixtures. The AASHTO T-322 test method was utilized for determining the creep compliance and tensile strength of the mixtures using the Superpave Indirect Tensile Test (IDT). The test specimens were compacted using the Superpave gyratory compactor. The surface mixture was compacted to 96% of maximum density while the interlayer mixture was compacted to 97% of maximum density. The surface mix was designed, tested and constructed at compaction effort of 60 gyrations, whereas 50 gyrations were utilized for the interlayer mixture. The IDT creep curves were shifted using the time-temperature superposition principle to form the creep compliance master curve. A ten-term generalized Voight-Kelvin model was fitted through the data. Using the fitted Voight-Kelvin model, the relaxation modulus of the mixtures were determined using interconversion techniques. Viscoelastic material properties in the form of generalized Maxwell model parameters are presented in Table 1. Also presented in Table 1 are the tensile strengths of the mixtures at -10°C.

To enable fracture modeling and evaluation, it was necessary to conduct material fracture characterization for the GPRA materials. Previous studies by Wagoner et al. [3-5], Song et al. [6,7], and Dave et al. [8-10] have demonstrated the principles of asphalt concrete fracture energy measurement and its utilization in rigorous fracture mechanics based simulation models. These studies have also demonstrated the successful prediction of thermal and reflective cracking in asphalt pavements and overlay treatments using these tools. The disk-shaped compact tension (DC(T)) test for asphalt concrete developed by Wagoner et al. [4] has been standardized as ASTM D7313-07b. The DC(T) test was utilized for fracture characterization of the overlay material from Taxiway-E rehabilitation. Material samples were not available at the time of fracture testing for interlayer mixture. The fracture energy of interlayer mixture was estimated based on DC(T) measurements performed on similar mixtures. The measured fracture energy for the overlay mixture and the estimated one used for simulation of the interlayer mixture are presented in Table 1.

FINITE ELEMENT ANALYSIS

Finite element analysis is widely being utilized in the design and analysis of highway and airfield pavements. For example, the latest FAA pavement design procedure, FAARFIELD, is based on 3D finite element analysis modeling. In the present study, finite element analyses were conducted for a simulated treated and untreated control section of Taxiway-E. The main objective of the modeling presented herein was to evaluate the thermal and reflective cracking potential of treated and untreated pavement sections. The terminology ‘treated section’ refers to the fiberglass grid and strain tolerant interlayer hybrid system that was described in a previous section.

Table 1. Overlay and Interlayer Material Properties.

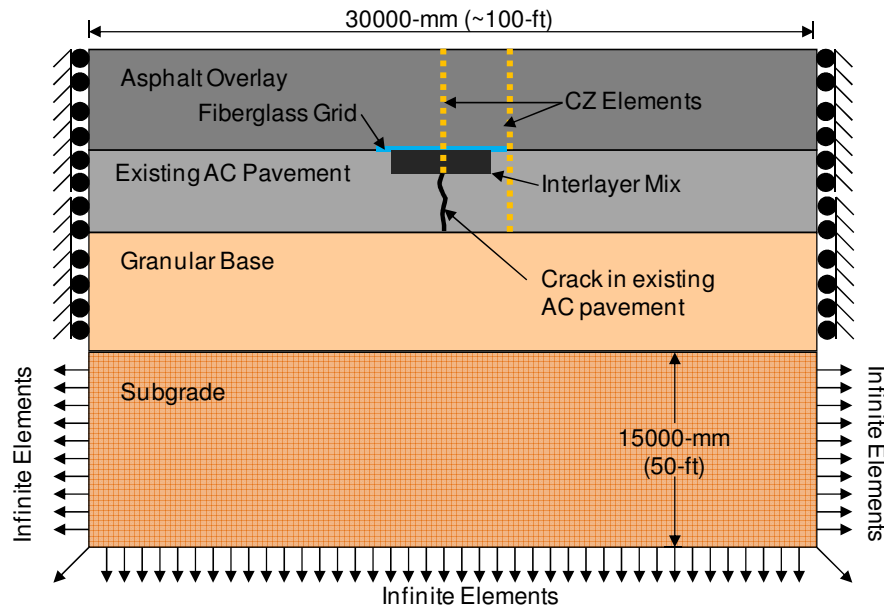
Interlayer					Overlay			
Spring Constants (MPa)					Relaxation Times (sec)			
Prony Series Parameters	E ₁	5069	τ_1	11.2	E ₁	4433	τ_1	15.1
	E ₂	3485	τ_2	178	E ₂	6208	τ_2	234
	E ₃	2390	τ_3	2888	E ₃	5040	τ_3	4062
	E ₄	2781	τ_4	34639	E ₄	6163	τ_4	40303
	E ₅	3346	τ_5	1348114	E ₅	3422	τ_5	1132144
Temperature, C					Log (Shift Factor)			
Shift Factors	-20				0			
Ref. Temperature = - 20C	-10				1.6			
	0				3.35			
Tensile Strength (MPa)	4.16				3.56			
Temperature = -10 C								
Fracture Energy (J/m ²)	3430*				448			
Temperature = -10 C								

* Value estimated based on fracture energy measured for similar mixture.

In recent years significant progress has been made concerning cracking simulation of asphalt pavements. A fracture mechanics based simulation approach called cohesive zone fracture model has been implemented and widely utilized for thermal and reflective cracking simulations [8-10]. The cohesive zone modeling (CZM) approach allows for accurate representation of highly non-linear fracture process zone (FPZ) that forms between the actual crack tip (also referred to as macro crack tip) and undamaged material. Linear elastic fracture mechanics (LEFM) type approaches ignore the formation of a FPZ and assume that the material behaves in purely brittle manner. Laboratory fracture energy measurements [3,4] have clearly shown that asphalt concrete exhibits significant post-peak softening behavior, making it quasi-brittle in nature. The CZM is implemented in the form of interfacial finite elements, or cohesive zone elements that can be inserted between bulk elements. This allows for simulation of crack initiation and propagation, and hence can be utilized to evaluate cracking potential in a pavement system.

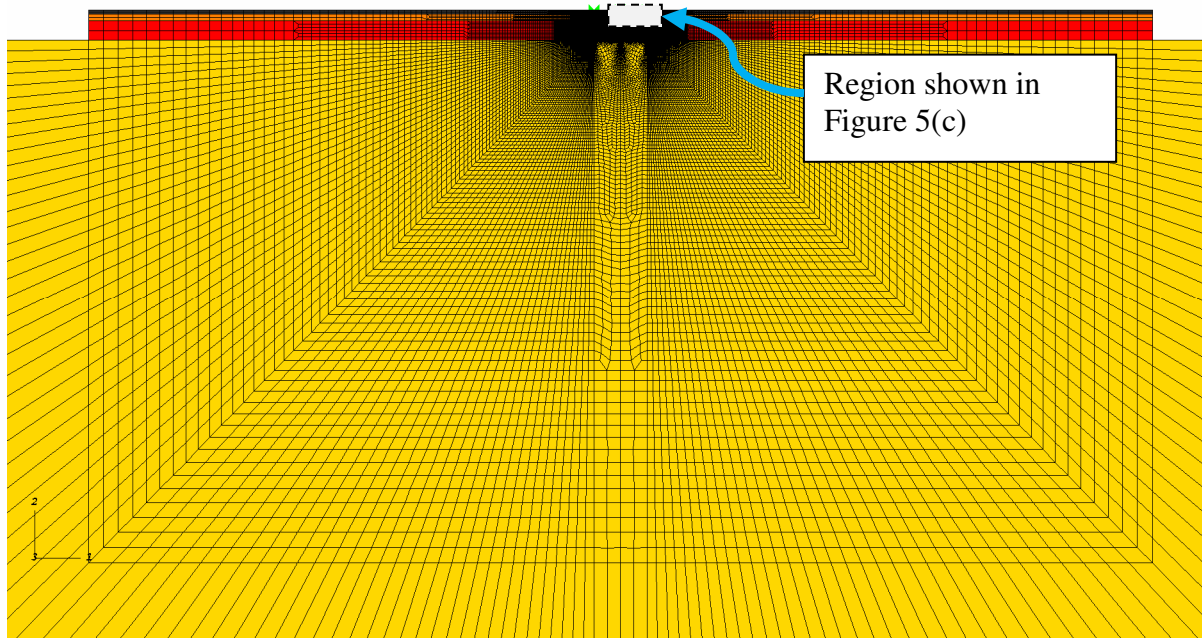
Finite element analysis for the present study were conducted using the commercial software *ABAQUS*. Several customizations to the commercial code were implemented through the use of user subroutines. These include cohesive zone elements, automatic thermal boundary condition application, and time-temperature shift factors for the viscoelastic materials. The pavement simulation model was developed with two-dimensional (2D) plane strain assumption. The primary direction of cracking is expected to be in the transverse direction; hence the 2D model was generated along the longitudinal direction of the simulated taxiway. Infinite elements were utilized to represent the semi-infinite nature of subgrade, and a time and temperature dependent viscoelastic constitutive model was used to capture the behavior of asphalt concrete at low temperature. Another important feature of the pavement model was the use of frictional interfaces between asphalt concrete layer and granular base and the granular base layer and the subgrade. The finite element mesh, model domain, and other features of the model are shown in

Figure 5. Notice that the cohesive zone elements are embedded in the model at two locations, directly above the underlying crack in the existing AC and just above the edge of the fiberglass grid. Previous studies on the use of reinforcing grids and stress absorbing treatments has showed reflective crack formation along the edge of treatments, which has been commonly referred to in the literature as “crack offsetting.” The cohesive zone elements were inserted along a vertical line at both locations, in order to simulate a vertically-oriented reflective crack. This limited simulations to consider pure mode I opening fracture. Although aircraft loads would create a shearing condition leading to mixed-mode cracking (and non-vertical crack propagation), the simulation of mixed-mode cracking is far more difficult, requiring more sophisticated lab testing and modeling techniques. To avoid this complexity, a tire load was centered over the reflective crack site to minimize shearing response and to facilitate a mode-I cracking simulation. A more detailed description of the induced loading conditions is presented in a later section. The model domain, boundary conditions, and interface conditions were determined based on domain extent studies reported in previous studies on reflective and thermal cracking simulations of asphalt pavements [8-10].

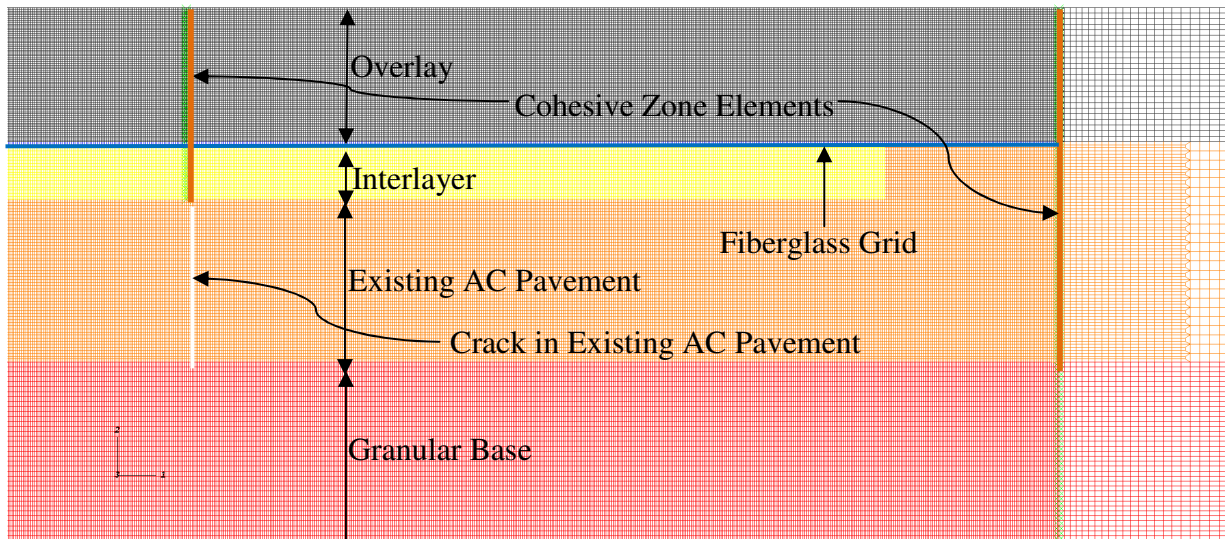


Note: Thickness of various pavement layers are same as shown in Figure 2. In case of control section interlayer mix and fiberglass grid does not exist.

(a) Schematic of Finite Element Model



(b) Finite Element Mesh for the Model (Total Elements: 295723, Total Nodes: 301548)



(c) Finite Element Model Attributes in Vicinity of Underlying Crack

Figure 5. Finite Element Pavement Model

Thermal stress build up in an overlay is thought to be an important contributor in the formation of reflective cracks. Critical cooling events are often associated with the occurrence of cracking in overlays [11]. It is important to accurately determine the temperature variation with

time and depth of pavement to accurately impose the temperature loading conditions. Thermocouple data captured at GPRA was used for calibration and verification of pavement temperatures predicted using the enhanced integrated climatic model (EICM) [12]. EICM is a mechanistic heat flow model that calculates the temperature distribution within a pavement by analyzing atmospheric climatic data in conjunction with structural layering and material property information using a finite-difference approach. Measured air and pavement temperature data at GPRA was utilized to calibrate the unknown asphalt concrete heat-flow material properties required by the model; particularly, heat capacity and thermal conductivity. The calibrated asphalt concrete properties are shown in Table 2. Although the calibrated material properties were outside of the typical range [12], nevertheless, the EICM predictions were within 1°C of the measured temperatures after this calibration.

Table 2. Calibrated Asphalt Concrete Thermal Properties.

	Overlay Mixture	Interlayer Mixture	Recommended Range [12]
Thermal Conductivity (cal/cm-hr-°C)	2.23	2.23	6.5 to 12
Heat Capacity (cal/gm-°C)	0.05	0.05	0.22 to 0.4

In order to identify a critical cooling event for use in simulation, EICM predicted pavement surface temperatures were analyzed for the period of time from August 2000 to August 2008. Based upon the peak cooling rate and the absolute lowest pavement surface temperatures predicted during this time period, a critical cooling event was identified as January 30th 2004 – January 31st 2004. The temperature variation through the asphalt pavement layers (overlay, interlayer, existing asphalt concrete) during the cooling event is shown in Figure 6. In order to minimize the effect of initial temperature conditions, the simulation was started at 12 pm on January 29th, 2004. When the coldest pavement surface temperature conditions were reached (surface temperature = -17.7°C), which was found to occur at 5 AM on January 31st 2004, a tire load was imposed. The tire loading conditions were evaluated based on the McDonnell Douglas, MD-88 main landing gear. The FAA advisory circular (AC 150/5320-6D) was utilized to determine the tire pressure as 1172 kPa and main gear load of 318 kN for this gear configuration. In order to study both types of reflective cracks, ones forming directly above the underlying crack as well as offset cracks that form along the edge of the reflective crack relief treatment, two loading cases were simulated: 1) tire loads centered directly over the underlying cracks, and; 2) tire loads centered over the edge of the fiberglass grid.

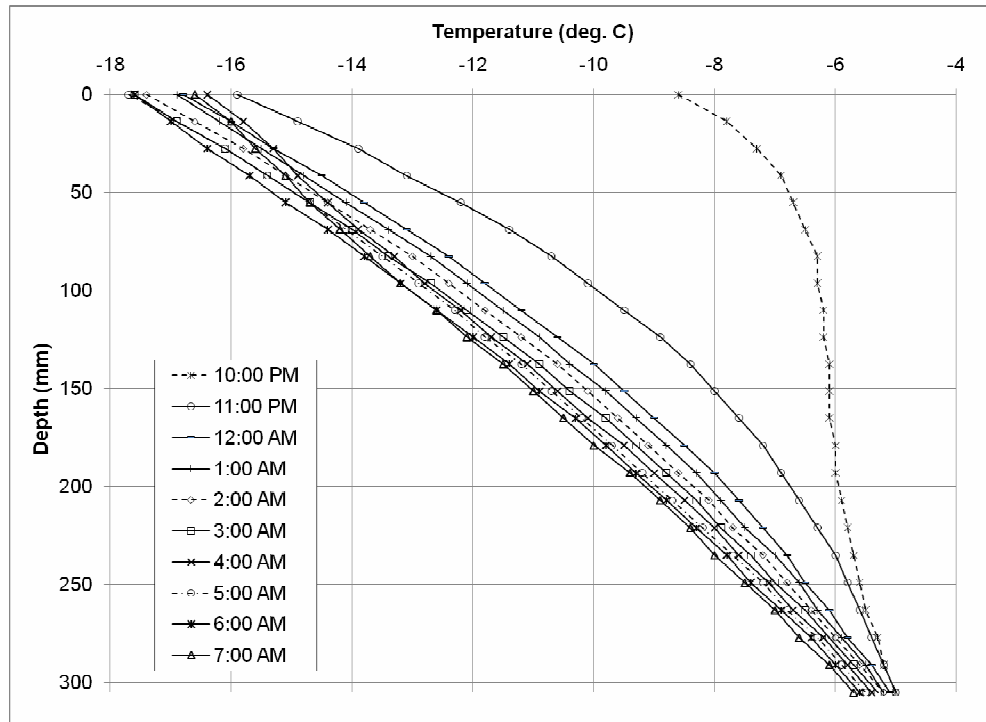


Figure 6. Pavement Temperature Profiles during the Simulated Critical Event

Simulation results were post-processed to compute the extent of damage (softening) and cracking (complete material separation) that occurred as a function of the thickness of the asphalt overlay. Previous studies have demonstrated a good correlation between the extent of simulated crack/damage forming during a critical cooling event and field performance [13]. The extent of damage and cracking for the series of simulations performed in this study are presented in Table 3. The simulated tire loading along the edge of the fiberglass treatment resulted in significant damage within the overlay, particularly for the control (untreated) section. In simulations of the control section, significant damage was predicted throughout the thickness of the overlay and a partial-depth (23% of thickness) bottom-up reflective crack was predicted. For the treated section, 19% of the thickness of the overlay was predicted to become damaged from the passage of a single gear loading during the critical cooling event. This indicates that there is offset cracking potential within the treated section under repeated gear loading. It should be noted that during simulations of temperature loading only, neither the treated or untreated section were predicted to undergo softening or damage. Overall, these results suggest that the treated crack locations at GPRA would slowly develop reflective cracking over time, as the combined effects of gear loading and temperature cycles would lead to progressive reflective crack development emanating from damaged regions of the overlay under combined thermo-mechanical loading.

Table 3. Simulation Results: Extent of Asphalt Layer Thickness Damaged and Cracked.

Section (Tire Load Location)	Extent of Overlay Thickness	
	Damage (Softening)	Cracking (Complete Separation)
Control (Centered over underlying crack)	75%	23%
Treated (Centered over underlying crack)	3%	0%
Treated (Centered over edge of grid treatment)	19%	0%

FIELD CRACKING PERFORMANCE

Taxiway-E at GPRA was surveyed periodically to determine the extent of cracking. Field cracking data for the pavement prior to the rehabilitation was also collected. Figure 7 shows cracking performance in terms of the amount of cracking normalized against the center-line length of the section. Notice that the two left hand side bars represent the amount of cracking in existing pavement prior to rehabilitation. The reduction in amount of cracking for existing pavement is attributed to 50 mm of milling that was conducted to accommodate the strain tolerant interlayer mixture. The location of existing cracks prior to treatment was noted during the initial crack surveys. During subsequent surveys, the location of cracks were compared with the underlying cracks to evaluate the extent of reflective cracking versus other cracking modes such as thermal and block cracking. Using this information the percent of reflected cracks were determined, this information is plotted in Figure 8. The plot indicates an escalation in the reflective cracking between 2004 and 2007. An important observation from the crack count surveys was the appearance of the reflected cracks. A significant number of reflective cracks were observed to have formed in a tortuous manner with low to medium severity; Figure 9 shows pictures of typical reflection cracking in the treated section from a 2009 survey. Notice that the formation of this type of distributed cracking might be attributed to the grid reinforcement and strain absorbent interlayer which could lead to formation of offset cracking and/or dissipation of the underlying crack movement over a greater area.

Despite the relatively high extent of reflective cracking now present, the reflective crack control system appears to have significantly improved the performance of the current overlay as compared to those of previous overlay cycles, which required rehabilitation in the form of an HMA overlay after seven years. Before rehabilitation in 2000, Taxiway E had wide, cupped, cracks (Figure 2), with relatively poor ride quality and moderate FOD generation. With the current treatment method, the pavement has low to medium severity reflective cracking after nine years of service, excellent ride quality, and relatively low FOD generation. Furthermore, the reflective cracking retardation afforded by the treatment system is also expected to continue to providing benefits after the next overlay is placed.

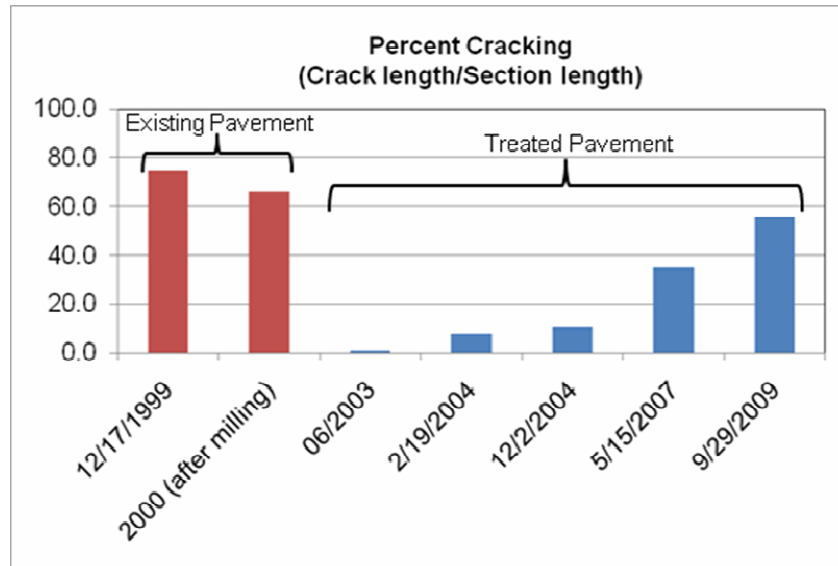


Figure 7. Cracking Performance of Taxiway-E at GPRA

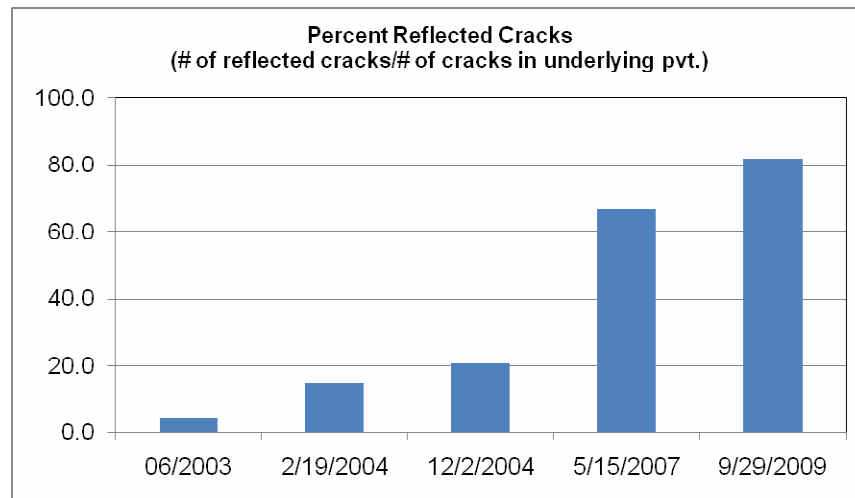


Figure 8. Reflective Cracking Performance of Taxiway-E at GPRA

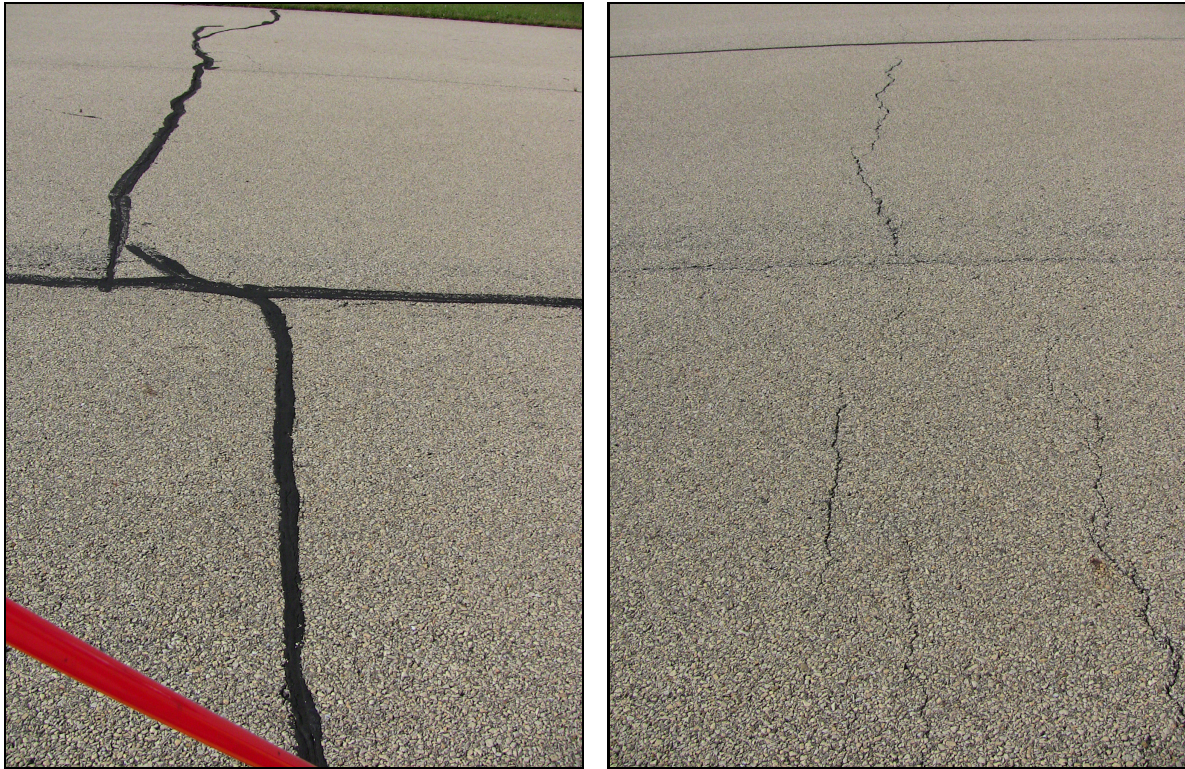


Figure 9. Typical Reflection Cracking in Treated Section after Nine Winters

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A case study involving rehabilitation of Taxiway-E at the Greater Peoria Regional airport is presented in this paper. The rehabilitation strategy involved use of a hybrid reflective crack relief system that is applied directly over the existing cracks in underlying pavement. The hybrid system integrates reinforcing grid and strain tolerant interlayer treatments. The grid system was selected to provide reinforcement over the crack and restrain movement under thermal and tire loading conditions, whereas the strain tolerant interlayer mixture was selected and designed to absorb local straining generated directly in the vicinity of underlying crack. Furthermore, the interlayer mixture was designed to prevent water infiltration into the pavement through the underlying crack.

Finite element simulations were conducted for treated and control sections and simulation results are discussed. The simulation results indicated limited reflective cracking potential for treated sections in traditional manner whereby reflective crack is formed directly above the underlying crack or discontinuity. However, the simulations indicated moderate potential for cracks to form along the edge of the grid treatment. High reflection crack potential was predicted for control section. Field cracking performance data was collected through crack count surveys. After nine winters of service the rehabilitated pavement has performed reasonably well. Delay of reflection cracking formation of four to seven years was observed. In case of treated section significant number of reflection cracking was observed to have formed in form of distributed

cracking and/or offset cracking. This might be indicative of the stress distribution generated by fiberglass grid and strain tolerant interlayer mixture.

Based on the material testing, field data sampling and finite element simulations following conclusions can be inferred:

- Reliable temperature profiles can be predicted using the enhanced integrated climatic model if the material properties are calibrated using the thermo-couple data.
- A hybrid reflective crack relief system comprising of fiberglass reinforcing grid and strain tolerant asphalt interlayer mixture is viable from construction perspective.
- Finite element analysis utilizing cohesive zone fracture model and elements can be utilized to explore the cracking potential and mechanisms in asphalt pavements with and without reflective crack resistant treatments.
- The simulation results qualitatively exhibited that there is potential for offset cracking in treated sections; this has been validated to through observation of slowly forming, low-severity reflection cracks on the pavement surface.

The simulation results and field performance data provided significant insight on the reflective crack formation in pavements treated with the hybrid system discussed in this paper. Based on the simulation results and field observations following recommendations can be made:

- The hybrid treatment system provides good reflective cracking resistance by isolating the local straining and reinforcing against excessive movement under tire and thermal loading. The current overlay is significantly outperforming the previous HMA overlay and is expected to provide additional protection against reflective cracking in future overlay cycles.
- In the present study the hybrid treatment is applied only at the existing crack locations, an area-wide treatment approach may further improve cracking performance and eliminate offset cracking.
- In the simulation models perfect bonding was assumed between the fiberglass grid and the asphalt layers above and below it. Laboratory characterization is needed to evaluate the mechanical characteristics of this bond, which can in turn be used to upgrade the finite element model.
- The effect of aging on the asphalt pavement was not accounted in the present study. As a future extension, aging effects should be accounted for and field samples should be obtained to accurately quantify this effect.

REFERENCES

1. Dave E. V., and W. G. Buttlar, "Thermal Reflective Cracking of Asphalt Concrete Overlays," *International Journal of Pavement Engineering*, Vol. 11, No. 3, 2010.

2. Kim, J., and W. G. Buttlar, Analysis of Reflective Crack Control System Involving Reinforcing Grid over Base-Isolating Interlayer Mixture, *ASCE Journal of Transportation Engineering*, Vol. 128, No. 4, pp. 375-384, 2002.
3. Wagoner, M. P., W. G. Buttlar, and G. H. Paulino, "Development of a single-edge notched beam test for asphalt concrete mixtures," *Journal of Testing and Evaluation, ASTM*, Vol. 33, No. 6, pp 452-460, 2005.
4. Wagoner, M. P., W. G. Buttlar, and G. H. Paulino, "Disk-Shaped Compact Tension Test for Asphalt Concrete Fracture," *Experimental Mechanics*, Vol. 45, pp 270-277, 2005.
5. Wagoner, M. P., W. G. Buttlar, G. H. Paulino, P. B. Blankenship, "Laboratory testing suite for characterization of asphalt concrete mixtures obtained from field cores", *Journal of Asphalt Paving Technologists, Association of Asphalt Paving Technologists*, Vol. 75, pp. 815-852, 2006.
6. Song, S. H., G. H. Paulino, and W. G. Buttlar, "Simulation of crack propagation in asphalt concrete using an intrinsic cohesive zone model." *Journal of Engineering Mechanics*, Vol. 132, No. 11, pp. 1215-1223, 2006.
7. Song, S. H., G. H. Paulino, and W. G. Buttlar, "A bilinear cohesive zone model tailored for fracture of asphalt concrete considering viscoelastic bulk material." *Engineering Fracture Mechanics*, Vol. 73, No. 18, pp. 2829-2848, 2006.
8. Dave, E. V., S. H. Song, W. G. Buttlar, and G. H. Paulino, "Reflective and Thermal Cracking Modeling of Asphalt Concrete Overlays," *Proceedings of the Advance Characterization of Pavement and Soil Engineering Materials – 2007 (Athens, Greece)*, pp. 1241-1252, 2007.
9. Dave, E. V., A. F. Braham, W. G. Buttlar, G. H. Paulino, and A. Zofka, "Integration of Laboratory Testing, Field Performance Data, and Numerical Simulations for the Study of Low-Temperature Cracking," *Proceedings of the 6th RILEM International Conference on Cracking in Pavements*, Chicago, USA, pp. 369-378, 2008.
10. Dave, E. V., and W. G. Buttlar, "Low Temperature Cracking Prediction with Consideration of Temperature Dependent Bulk and Fracture Properties," *submitted to Road Materials and Pavement Design*, 2010.
11. Apeagyei, A. K., E. V. Dave, and W. G. Buttlar, "Effect of Cooling Rate on Thermal Cracking of Asphalt Concrete Pavements," *Journal of Association of the Asphalt Paving Technologists*, Vol. 77, pp. 709-738, 2008.
12. Larson, G., and B. J. Dempsey, "Enhanced Integrated Climatic Model: Version 2.0", Report DTFA MN/DOT 72114, Minnesota Road Research Project and Federal Highway Administration, 1997.
13. Paulino, G. H., W. G. Buttlar, P. Blankenship, M. P. Wagoner, S. H. Song, and E. V. Dave, "Final Report: Project 0219566, GOALI: Reflective Crack Control Treatment and Design Procedures: A New Integrated Approach," National Science Foundation, 2006.